COMPARATIVE ANALYSIS OF KAZAKHSTANI AND EUROPEAN APPROACHES FOR GEOTECHNICAL DESIGN OF SHALLOW AND DEEP FOUNDATIONS

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Declaration

I hereby, declare that this manuscript, entitled "Comparative Analysis of Kazakhstani and European Approaches for Geotechnical Design of Shallow and Deep Foundations", is the result of my own work except for quotations and citations which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

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Abstract

This research project considers the problems of the integration of European standards in Kazakhstan. The introduction of Eurocode in the construction sector experiences the difficulties associated with the adaptation of project documentation to local regulatory systems and the application of innovative construction technologies that do not conform to national SNiP-based regulations. The advantages associated with the harmonization of the Kazakhstani and European approaches include the application of innovative construction technologies in the country and the elimination of technical barriers between local and foreign specialists. The harmonization of national and European design codes represents a gradual process, which requires careful consideration. Thus, the significance of the study of international design code and its design methods arises. This research work is dedicated to providing technical background on the application of Eurocode 7 and performance of the construction works following international standards in Kazakhstan.

The main idea of this study refers to the comparison of Kazakhstani and European approaches for the geotechnical design of shallow and deep foundations (i.e., pad, strip, raft, pile, and piled raft). The design of different foundation types is performed by SP RK 5.01-102-2013 «Foundations of buildings and structures», SP RK 5.01-103-2013 «Pile foundations», and Eurocode 7: Geotechnical design for the design problem in Nur-Sultan, Kazakhstan. The over-design factor, bearing resistance, and elastic settlement are calculated adhering to both Kazakhstani and European approaches. Based on the performed comparative analysis it is identified that Eurocode provides more conservative results – thus, higher safety level, - compared to the Kazakhstani building regulations. The sensitivity analysis presenting the change of the bearing resistance values on different foundation parameters is given to support the conclusions about Eurocode conservativeness.

The difference between the estimated results is explained by the application of higher partial safety factors by Eurocode 7. Moreover, the European approach combines the design methods and traditions of various EU-countries, which contributes to a more conservative geotechnical design compared to the Kazakhstani approach.

Keywords: shallow foundation, raft foundation; pile foundation; piled raft foundation; bearing resistance; elastic settlement; SNiP; SP RK; Eurocode 7

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CHAPTER ONE: INTRODUCTION

1.1 Background

The continuous development of the construction industry, as well as construction materials and design techniques in Kazakhstan, requires the building regulations to conform to modern economic conditions, current legislation system, and changing environment. Moreover, the globalization process requires the application of unified regulatory standards that contribute to the creation of common requirements for product manufacturing and services on an international level.

The construction process is associated with the selection of building standards and design codes as the constructor's attention is always attracted by the questions of quality and durability of buildings and structures in both technical and economic aspects. The national building regulatory system involved the application of a complex design code that has been developed during the times of the Soviet Union (Tolybekova, Dyusebayev, & Besimbayev, 2016). The actualization of the existing building regulations has been performed and the transition to national standards SN RK EN identical to Eurocode has been initiated.

The need for the introduction of Eurocode into the construction area in Kazakhstan is explained by the requirement of the improvement of quality and safety of the constructed buildings and structures and the produced construction materials. Besides, the European code of practice considers all innovative construction materials and design technologies compared to outdated SNiP-based methods (Tolybekova, Dyusebayev, & Besimbayev, 2016). The additional advantage of Eurocode is related to the consideration of not only static and dynamic loads but also serviceability loads by the application of partial factors of safety. Thus, the design results obtained following the European code exceed the SNiP values, which means that Eurocode allows obtaining more stability, safety, and durability to the designed buildings and structures (Zhakulin et al., 2016).

The transition from the existing building regulations to Eurocode is supported by the intention of Kazakhstan to integrate into the world economic system. The harmonization of Kazakhstani building regulations and construction processes with the codes of practice of the developed countries allows (1) the improvement of the interchange of services in the construction field between the involved countries and (2) the increase of the competitiveness of local specialists and manufacturers of construction materials on the international market. Moreover, the introduction of European building standards attracts foreign investors and construction companies for the implementation of international projects on the territory of Kazakhstan.

1.2 Scientific novelty and significance of the research

The rapid urbanization process as well as strong economic growth contributed to the development of the construction sector in Kazakhstan over the last decades (Makhmutova, 2018). The progress in the construction sector positively affects the living standards and safety of the Kazakhstani population (Antonova et al., 2014). Moreover, the development of the construction industry in the country contributes to the economic development of various adjacent spheres in Kazakhstan (Bazarbayev & Ibraimova, 2016). The government encourages the implementation of extensive and expensive projects and attracts foreign construction companies for their realization in Kazakhstan (Lambla, 2019). The national building regulatory system is still applying the SNiP-based design code that has not been modified for many years and does not allow the employment of innovative design technologies to implement international projects in our country (Kutuzov, 2012). The application of an outdated system of building regulations results in the lack of competitiveness of local companies on the world market and causes difficulties for the development of the construction industry in Kazakhstan overall (Tolybekova, Dyusebayev, & Besimbayev, 2016).

The current situation in the construction industry can be solved by the harmonization of international and national design codes. The initiative on the introduction of Eurocodes into the national regulatory system refers to the 49th step of the national plan “100 specific steps” for the implementation of five institutional reforms of Nursultan Nazarbayev, the first president of the Republic of Kazakhstan (Bisengaliyev, Zaydemova, & Mukhambetzhanova, 2019). The process of adaptation of the European code of practice has been started since 2010 for the implementation of international projects. Since 2011, Eurocodes have been introduced on the territory of Kazakhstan and are applied in parallel with national building regulations. Eurocodes represent European technical regulations developed by the European Committee for the design of buildings and structures for civil purposes (Frank, 2007). European approach allows (1) applying advanced scientific and technical achievements of the developed countries, (2) introducing innovations, results of scientific research and design developments, and (3) stimulating scientific research.

The variety of the design methods for the implementation of buildings and structures adhering to international building regulations including American Association of State Highway

Transportation Officials (AASHTO), Eurocode, and Canadian Highway Bridge Design Code, cause problems for the construction project documentation to be adapted to local building regulatory system. The problems of technical regulation of the construction sector are also related to the gradual transition process in Kazakhstan. Nowadays, the production and quality control of construction materials is impeded due to the lack of common criteria for the assessment of construction materials. The harmonization of Kazakhstani and European codes allows the consideration of general requirements for the production of construction materials, as well as their classification, testing methods, and other characteristics.

Eurocodes are used for the calculation of all types of buildings and structures under all types of loads and effects as well as different combinations of actions and cover all types of construction materials including concrete, steel, masonry, wood, and aluminum (Orr, 2013). However, the SNiP-based approach does not consider the application of modern innovative technologies that slows down the development of the construction industry in Kazakhstan. Moreover, Eurocodes, widely applied in more than 45 countries, provide an opportunity for all countries to consider national features (i.e., climatic, seismological, geotechnical, level of technical and economic development, etc.) in National Annexes (NAs). The major difference between the considered approaches refers to the wide range of Eurocode applications compared to Kazakhstani building regulation. Eurocodes provide the procedure for the calculation of the design parameters, whereas the SNiP-based design standard provides both the parameters and engineering methods for calculation. Therefore, the application of Eurocodes requires a higher level of qualifications of the engineers. The need for a new educational approach for the preparation of specialists arises.

Adaptation of Eurocode in Kazakhstan allows eliminating technical barriers in international collaborations and creating the unified normative system of technical regulation for the implementation of construction works. The harmonization of Kazakhstani building regulations with Eurocodes will result in identical computing methods and common requirements for the design of buildings and structures, similar calculation results, as well as a common research area. The objectives of the harmonization include (1) convergence of scientific bases and design approaches; (2) coincidence of the construction requirements and (3) identity of the calculation results when designing and constructing buildings and structures. Also, this will enable local manufacturers of construction materials to (1) enter the European market, (2) produce products that meet European standards, (3) provide the construction and engineering services in the EU countries and (4) reduce the costs of European certification of building materials and products in Kazakhstan.

The possibility of the application of international standards on the territory of our country creates new opportunities for the integration of Kazakhstan into the European economy. The process of study of European code and its introduction in Kazakhstan stimulates the development of scientific and technical collaboration and communication with European specialists. Therefore, understanding the European approach for geotechnical and structural design is critical for facilitating the development of the construction industry in Kazakhstan (Almazov, 2011).

1.3 Objectives of the dissertation

SNiP-based technical regulations for geotechnical design of shallow, pile, and piled-raft foundations existing from the times of the Soviet Union provide less conservative results of bearing resistance and elastic settlement than Eurocode 7.

The objective of the proposed thesis work is to perform a comparative analysis of Kazakhstani and European approaches for the implementation of geotechnical design of buildings and structures in Kazakhstan. This research is intended to promote and advance knowledge on the application of Eurocode 7 among geotechnical engineers in Kazakhstan.

1.4 Scope of the study

This research work investigates the differences between the geotechnical design of shallow and deep foundations adhering to the Kazakhstani and European approaches. This study focuses on the design of pad, strip, raft, pile, and piled raft foundations by calculating the bearing resistance and elastic settlement from EC 7 and SP RK. In addition, the overdesign factor for both of the considered codes of practice is determined.

The design problem in Nur-Sultan city is presented for the calculation of bearing resistance and elastic settlement values for shallow and deep foundations adhering to the Kazakhstani and European approaches. The Nur-Sultan soil properties and soil profiles are considered in this study for the comparison of the bearing resistance and elastic settlement results.

CHAPTER TWO: REVIEW OF THE DESIGN CODES

2.1 Introduction

The rapid development of the construction industry in Kazakhstan involved the development of design methods and manufactured construction materials. The designer should pay attention to the durability and quality of the constructed building and structures by conforming to modern realities. The selection of the design code and standards, thus the design methods and techniques, play a significant role in the construction process. Therefore, the applied building regulation needs to conform to the up-to-date economic conditions, changing competitive environment of the construction sector, and current legislation system.

The process of globalization requires the development of a unified system of building regulations contributing to the creation of general requirements for the manufacturing of construction materials and providing construction services on the international level. This study covers the consideration of EC7 and SP RK, which represent the design codes applied on the territory of the EU-countries and Kazakhstan, respectively. The Kazakhstani construction industry is still applying the complex building regulations that have been developed during the times of the Soviet Union. As discussed in Chapter 1, the European design code is being adopted in Kazakhstan under the regulations of the national plan “100 steps”. The changes in the regulatory system include the transition to national standards SN RK EN identical to Eurocode.

The transition from the existing building regulation to Eurocode is explained by the intention of our country to integrate into the world economical market. The harmonization of the national code of practice with the construction experience of the developed European countries allows the interchange of construction services between EU-countries and Kazakhstan; increasing the competitiveness of the Kazakhstani construction companies and manufacturers of construction materials on the international market, as well as improvement of quality and safety of the constructed buildings and structures. That is why it is important to understand the structure and provisions of the regulatory system of the construction sector in our country, as well as familiarize yourself with the adopted code of practice.

2.2 Review of Kazakhstani building regulation

The state system of the normative documents in the field of architecture, urban planning, and construction represents a set of interconnected national regulations approved by the government following international agreements.

Kazakhstani building regulations include:

- Normative documents regulating the activities in the field of architecture, urban planning, and construction;
- Building regulations and design codes;
- Manuals and recommendations related to the field of construction;
- Codes of practice;
- Normative documents;
- National and international standards in the field of construction;
- Regulatory and technical documents of the state control bodies.

The SNiP-based technical regulations have been applied in Kazakhstan and other CIS countries for approximately 25-30 years (Volokh et al., 2017). SNiP represents a set of normative documents acting in the technical, economical, and legal direction. It is responsible for the implementation of urban planning, construction, architectural, and civil engineering activities. SNiP provides the requirements for the construction and maintenance of buildings and structures. The actualization of the existing building regulations has been performed and SNiPs have been replaced by new SN RK and SP RK. Since 2010, SNiP has been considered as SN RK and SP RK in Kazakhstan. This provided the possibility of the realization of the requirements and harmonized the national standards with innovative international codes of practice.

Currently, the hierarchy of the normative documents in the construction sector of the Republic of Kazakhstan consists of three levels as follows:

- *Level 1:* The Law of the Republic of Kazakhstan "About architectural, urban planning, and construction activities in the Republic of Kazakhstan" and The Law of the Republic of Kazakhstan "About technical regulation".
- *Level 2:* Technical regulation "The requirements to safety of buildings and structures, construction materials and products", which contains the minimum safety requirements, and SN RK, which provides the detailed requirements in addition to technical regulation about all aspects in the construction field.

- *Level 3:* SP RK and Normative and technical manuals, containing the links to the agreed standards.

The national plan “100 steps” suggested by the first President Nursultan Nazarbayev involved the realization of the Eurocodes in Kazakhstan instead of the outdated SNiP-based technical regulations. The adoption of Eurocode will encourage the application of innovative technologies and construction materials, increase the competitiveness of local specialists in the construction services market, as well as create opportunities for the Kazakhstani construction companies to implement complex construction projects abroad.

Since 2015, the harmonization process of the Kazakhstani building regulations with Eurocode has been initiated with the adoption of the national regulations SN RK EN identical to EC. SN RK EN satisfies the requirements of technical regulation “The requirements to safety of buildings and structures, construction materials and products”, such as (1) mechanical stability and strength; (2) fire safety; and (3) a part of safety during exploitation requirements. SN RK EN allows the design of foundations and bases of buildings and structures; and the bearing constructions of buildings and structures, as well as their serviceability including durability and economical aspects. Besides, the transition process requires time for the development of the National Annex of the Republic of Kazakhstan considering its climatic, geophysical, and seismic parameters of the country.

Figure 1 presents the hierarchical structure of the base for the national construction regulatory system. The building code of the Republic of Kazakhstan contains the parametric construction norms, which have socially valuable goals and describes the requirement for technical characteristics of the designed object. Any national, regional or foreign standards, including Eurocode, are applied in the form of the method of alternative solutions.

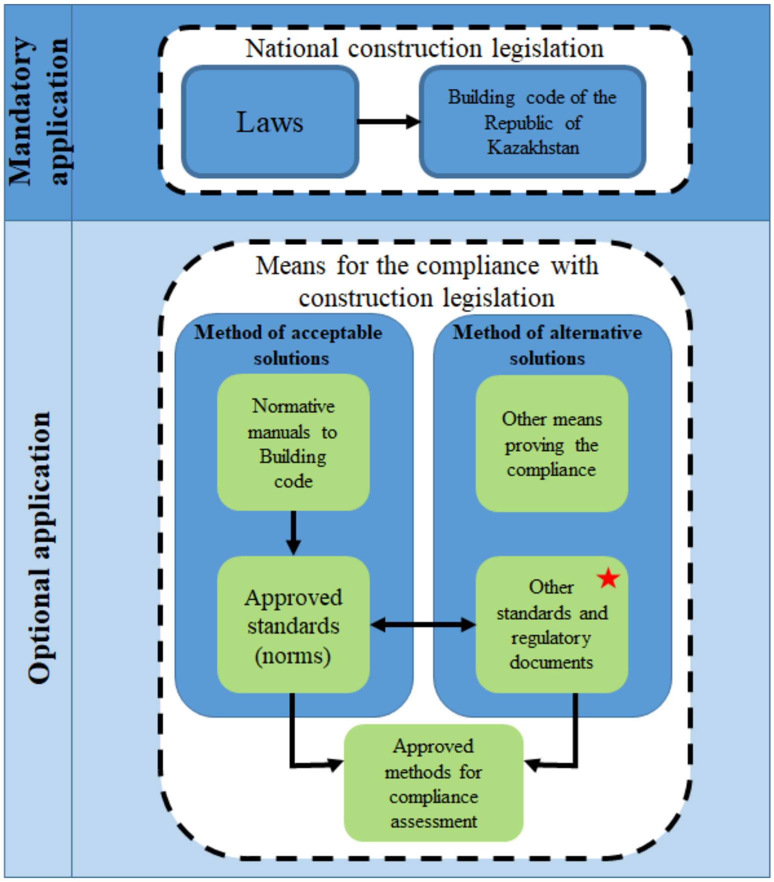


Figure 1: Hierarchical structure of the construction regulatory system of the Republic of Kazakhstan

2.3 Review of Eurocode 7

The Eurocode system represents a set of 10 interconnected technical regulations applied for all types of construction purposes (Frank, 2007). Eurocode contains the design methods and considers the safety and durability requirements. CEN (Comité Européen de Normalisation) took place in the development of Eurocode. Eurocode involves the application of the construction materials in the design of buildings and structures according to Euronorms, which represent CEN standards to materials and goods. To be more specific, Eurocode provides links to other European standards, construction materials, design, and testing methods widely applied by designers, constructors, and manufacturers in EU-member countries.

The Eurocode program includes the following standards, each of which contains several parts (Figure 2):

- Eurocode 0: Basis of structural design (EN 1990)
- Eurocode 1: Actions on structures (EN 1991)
- Eurocode 2: Design of concrete structures (EN 1992)
- Eurocode 3: Design of steel structures (EN 1993)
- Eurocode 4: Design of composite steel and concrete structures (EN 1994)
- Eurocode 5: Design of timber structures (EN 1995)
- Eurocode 6: Design of masonry structures (EN 1996)
- Eurocode 7: Geotechnical design (EN 1997)
- Eurocode 8: Design of structures for earthquake resistance (EN 1998)
- Eurocode 9: Design of aluminum structures (EN 1999)

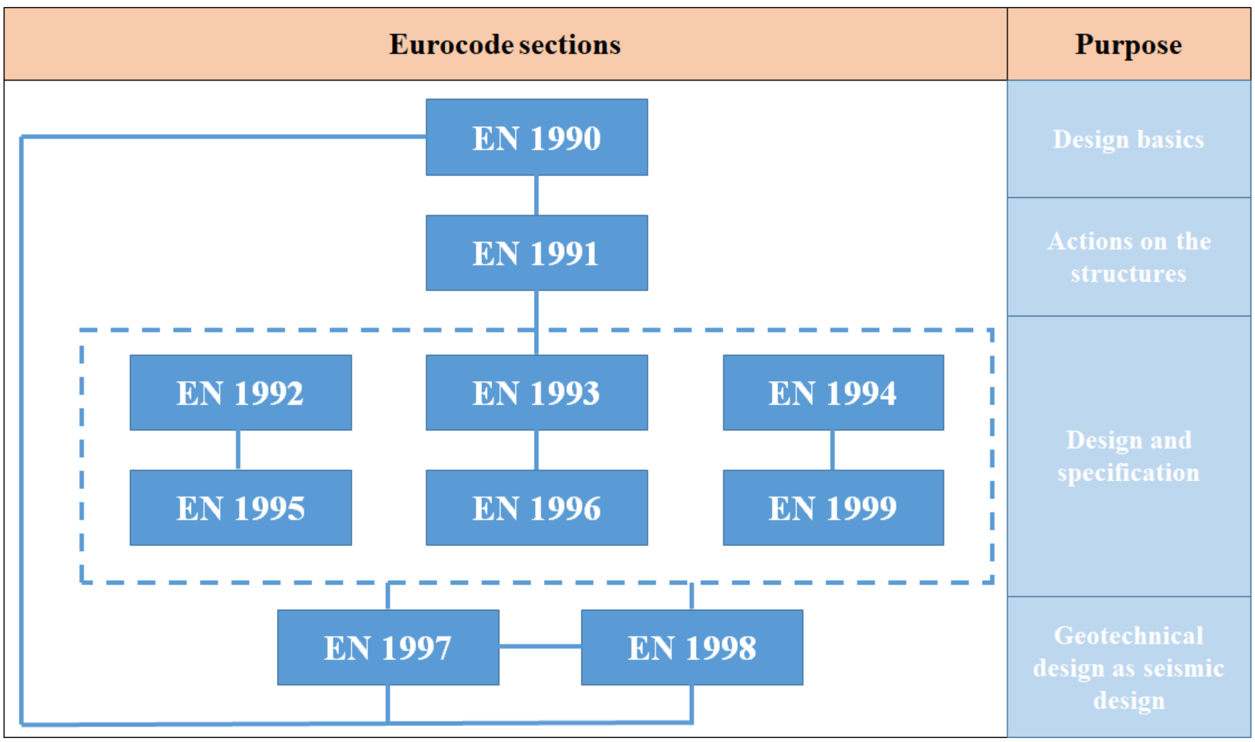


Figure 2: Eurocode structure

Eurocode is not designed for direct application and is required to be adopted for the local conditions. For this purpose, each country that applies Eurocode is intended to develop the National Annex (NA). The NA is developed in each European country to connect the Eurocode system with the national building standards (Schuppener, 2007). The objectives of NA include (1) definition of the partial safety factor values; (2) selection of the design approaches; and (3) development of the specifications regarding the application of the informative annexes.

Eurocode 7 (EC 7) represents a technical regulation within the Eurocode framework that harmonizes the geotechnical and structural designs of buildings and structures (Orr, 2006). This standard covers the design of the structures interacting with soil and rocks, including foundations, retaining structures, and bridges (Frank, 2007). EC 7 allows (1) determination of the design actions on the buildings and structure and design resistances of the soil; (2) provides the recommendations for the geotechnical design.

EC 7 contains two parts, such as Part 1: General rules and Part 2: Ground investigation and testing. EC 7-1 contains the sections covering the geotechnical design of structures in contact with the ground (i.e. shallow and deep foundations, anchorages, retaining walls, and embankments) on stability, as well as construction supervision and maintenance on soil improvement, dewatering, and reinforcement (Schuppener, 2010). The NAs do not modify the content of Eurocode 7 but provide the possibility of the selection of nationally determined parameters where it is allowed.

EC 7-1 represents a general document providing the geotechnical design principles based on the Limit State Design (LSD) approach. These principles allow the determination of the design actions applied to the building and structures and design of structural elements (i.e., foundations, piles, and walls). The informative Annexes provide the design charts and equations. As there is a difference between the design parameters and models in the European countries, Annex A just provides the recommended values of the partial factors to verify the Ultimate Limit State (ULS) design. The actual values of the partial factors are defined by the EU member countries in the NAs.

Moreover, three design approaches (DAs) are considered in EC 7-1 for the verification of geotechnical ultimate limit states. The main difference between the DAs refers to the way for the introduction of partial safety factors on actions, materials, and resistances. The selection of the DA is performed nationally based on construction experience and indicated in the NA (Bond, 2008). The distribution of design approaches in EU-member countries is provided in Figure 3.

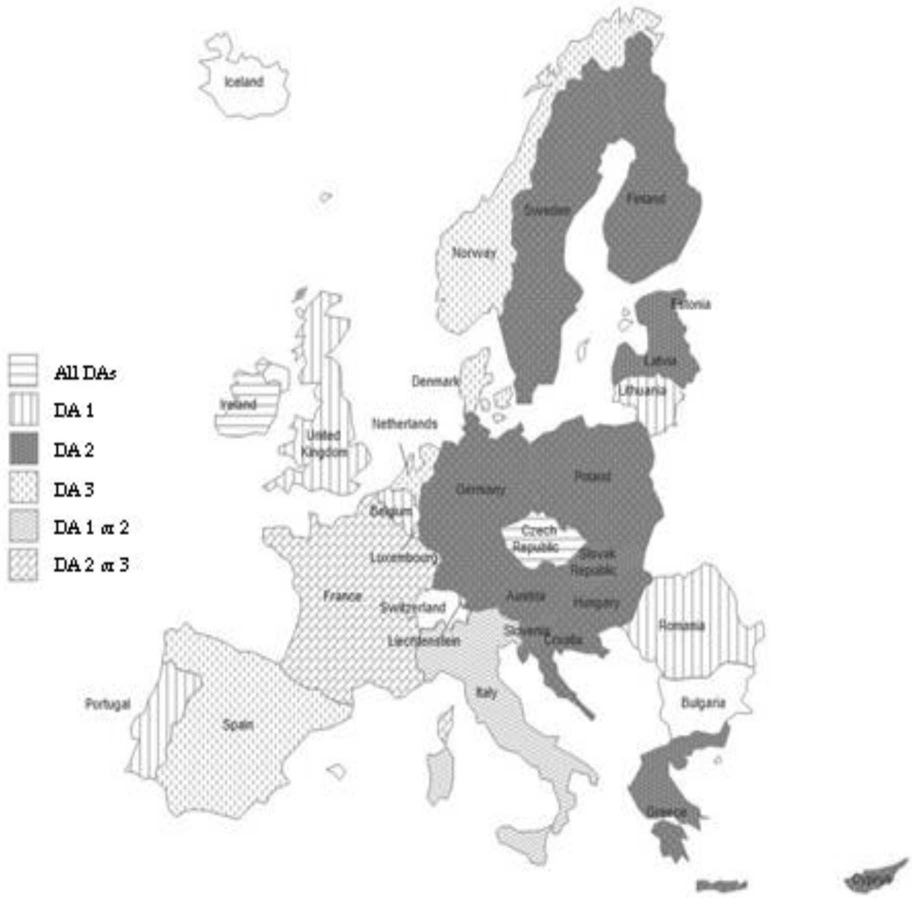


Figure 3: Distribution of design approaches in EU countries (Zhanabayeva et al., 2021)

- Design Approach 1

There are two combinations of partial factors given in DA 1. Combination 1 aims to provide a safe geotechnical design against unfavorable conditions for actions, whereas Combination 2 considers unfavorable conditions for soil strength properties. In DA 1-1 partial factor on permanent and variable loads (γ_G and γ_Q) of greater than unity are applied as for the structural design., In DA 1-2 partial factors on soil strength properties (γ_φ, γ_c and γ_{cu}) of greater than unity are applied as for the structural design. The recommended values of the partial factors are provided in Table 1.

- Design Approach 2

DA2 applies the partial safety factor on actions (γ_G and γ_Q) and design resistance (γ_b and γ_s), rather than on soil parameters. The recommended values of the partial factors are provided in Table 1. This design approach is based on load and resistance factor design (LRFD) design widely applied by the American design code (Bond, 2012).

- Design Approach 3

The partial safety factors are applied on actions (γ_G and γ_Q) and soil parameters (γ_φ, γ_c and γ_{cu}) simultaneously for DA3. The recommended values of the partial factors are provided in Table 1. Similar to DA1, DA3 applies the material strength design (MSD) method.

Table 1: Partial safety factors for Design Approaches (DAs) of Eurocode 7.

Design Approach	γ_G	γ_Q	γ_b	γ_s	$\gamma_{c'}$	$\gamma_{\varphi'}$
DA1-1	1.35	1.5	1.0	1.0	1.0	1.0
DA1-2	1.0	1.3	1.0	1.0	1.25	1.25
DA2	1.35	1.5	1.1	1.1	1.0	1.0
DA3	1.0	1.3	1.0	1.0	1.25	1.25

Table 2: Design Approaches (DAs) of Eurocode 7.

Design Approach	**Combination**
DA1-1	A1 + M1 + R1
DA1-2	A2 + M2 + R1
DA2	A1 + M1 + R2
DA3	A2 + M2 + R3

EC 7-2 is devoted to the planning, evaluation and applications of the laboratory and field testing results. This document complements the design requirements of EC 7-1 to ensure the safety and stability of the geotechnical design. The results of the laboratory and field tests are used as the input values for the EC 7-1 design models. EC 7-2 covers laboratory and field tests in soils and rocks, planning and reporting of ground investigations, and calculation methods.

2.4 Summary

The globalization of the world's economic and social spheres contributes to the development of the unified bases for the integration process. In the economic sphere, these bases are referred to as standards, which allow communication on the same technical language between the participants of the technical process and presentation of the identical requirements to the produced goods and services.

In accordance with the resolution of the Elbasy Nursultan Nazarbayev and the government, the reform of the technical regulation in the construction sector has been initiated since 2010. This action is intended by the desire of Kazakhstan to integrate into the world economic system through the harmonization with the experience of the developed countries. The base of the reforming of the technical regulatory system is presented by the gradual transition to the parametric principles with the adoption of the national regulations SN RK EN identical to EC.

The existing building regulations will be applied in Kazakhstan in parallel with EC. The reason is that application of Eurocode on the territory of Kazakhstan is limited by the design methods for proving the strength, durability and safety of the designed buildings and structures.

It is important to consider the climatic (wind and snow load, temperature changes, etc.) and geophysical (soil parameters, seismology, etc.) conditions when applying EC in Kazakhstan as they differ from the conditions in European countries. Moreover, the international responsibilities of Kazakhstan towards the contribution to CEN for adaptation of EC are required to be accomplished.

It is identified that Kazakhstani building regulations of Eurocode have different structure and contents and represent the documents with different format and status. However, the objective of their application is similar and refers to the providing safety of the designed structures in terms of mechanical stability and fire resistance by using different construction materials. Figure 4 shows the transition of several Commonwealth of Independent States (CIS) countries, including Kazakhstan, Russia, and Belarus, to Eurocode.

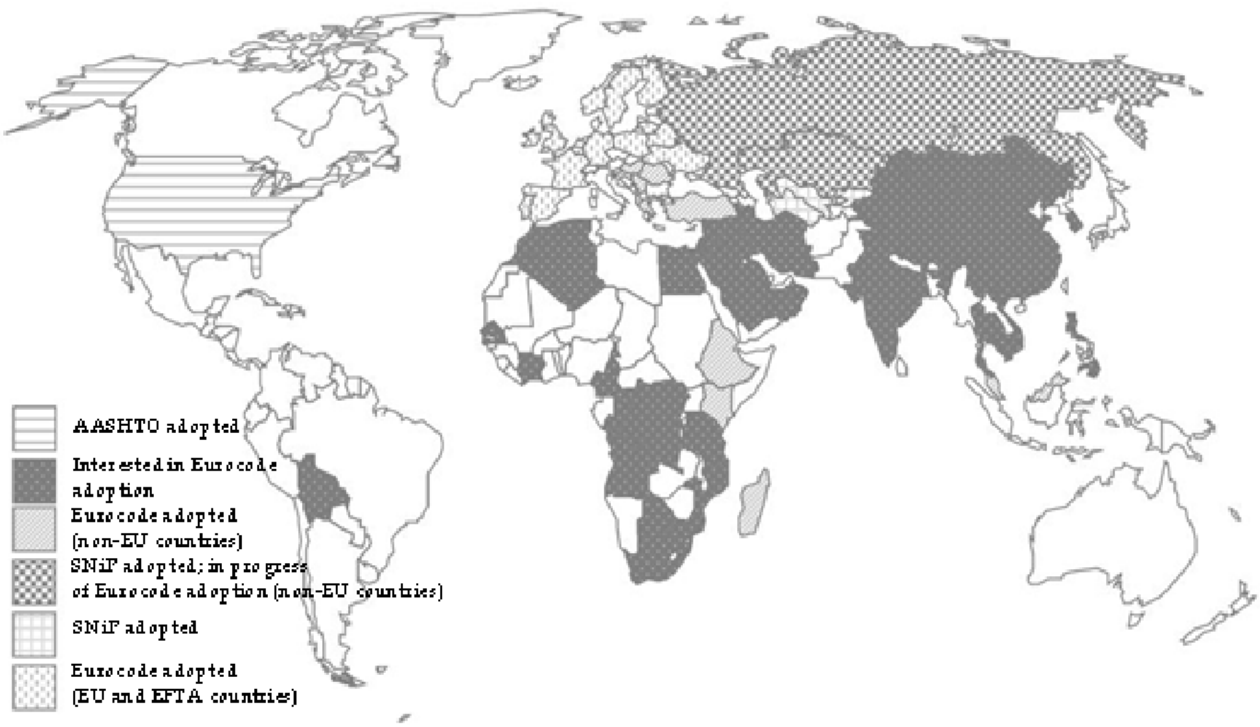


Figure 4: Distribution of design codes around the world (Zhanabayeva et al., 2021)

CHAPTER THREE: METHODOLOGY

3.1 Introduction

Eurocode 7 (EC 7) represents a geotechnical design code that is widely applied throughout the European Union (Frank, 2007). This building standard considers the design of buildings and structures in contact with the ground from retaining structures to foundations of different types. EC 7 allows the determination of geotechnical actions and resistances and provides the guidelines for the successful performance of geotechnical projects.

The objective of EC 7 involves the harmonization of design rules for geotechnical purposes in European countries by providing a unified code of practice (Orr, 2002). In addition, the harmonization of geotechnical and structural design has been achieved by the introduction of the limit state concept in EC 7.

EC 7 represents a practical tool that encourages the communication of geotechnical engineers in Europe in the same technical language (Frank, 2007). This design code provides general rules for the geotechnical design of buildings and structures and contains some calculation methods in the annexes by considering the geological and soil parameters of the European countries (Orr, 2013). Also, EC 7 provides the alternative for the selection of three Design Approaches (DAs) for the verification of geotechnical limit states.

Even though the origin of Eurocode is Europe, this code of practice can be applied worldwide for geotechnical and structural designs (Orr, 2002). The potential for the harmonization of EC 7 in other countries is great as it provides the possibility for the selection of different design approaches and partial safety factors values for the verification of geotechnical limit states (Schuppener, 2010).

Since 2014, Eurocode has been applied in Kazakhstan in parallel with the existing building regulations (Saparbayev & Tulebekova, 2019). The SN RK EN regulatory documents identical to Eurocode have been developed considering national climatic, seismic, and geological features. The transition process involved the translation of the European standard into Kazakh and Russian languages, comparison of the computation results, and development of the additional chapters covering the Kazakhstani features. The introduction and adaptation of Eurocode in Kazakhstan face the difficulties associated with the overcoming of the established traditional design approach (Kurmaniyazova, 2019).

This chapter presents an overview of the design methods for geotechnical design when adhering to the Kazakhstani and European approaches. The shallow and deep foundations computational procedure for the identification of bearing resistance and elastic settlement is provided. SP RK 5.01-102-2013 «Foundations of buildings and structures» and SP RK 5.01-102-2013 «Foundations of buildings and structures» are involved for the geotechnical design following the Kazakhstani approach, whereas Eurocode 7 is used for the European approach. Besides, the procedure for the calculation of the overdesign factor is presented to compare the design approaches in terms of conservativeness.

3.2 Overview of the design methods

3.3 Shallow foundation design

A shallow foundation represents a type of building foundation transmitting the vertical load from building to soil near the ground surface. Generally, the shallow foundation depth is equal or less to its least dimension (Smith, 2014). Pad, strip, and raft foundations are categorized as shallow foundations.

3.3.1 Determination of the bearing resistance of shallow foundation

The Kazakhstani geotechnical design approach suggests the computation of the bearing resistance of shallow foundations by the procedure provided in SP RK 5.01-102-2013 «Foundations of buildings and structures» (SP RK, 2015a). The ULS analysis of shallow foundation requires the following condition to be satisfied:

$$p \leq R \tag{1}$$

where p is the average design pressure under the shallow foundation base, kN; and R is the bearing resistance, kN.

The average pressure under the foundation base is determined in accordance with the following equation:

$$p = \frac{N + G_f + G_g}{b} \tag{2}$$

where N is the average pressure under the foundation base, kN/m; G_f is the foundation weight, kN/m; and G_g is the soil weight acting on the foundation slab, kN/m.

The Kazakhstani approach determines the bearing resistance of soil under the shallow foundation base by using the following equation:

$$R = \frac{\gamma_{c1}\gamma_{c2}}{k}\left[M_\gamma k_z b \gamma_{II} + M_q d_I \gamma'_{II} + (M_q - 1) d_b \gamma'_{II} + M_c c_{II}\right] \qquad (3)$$

Table 3: Description of the parameters in SP RK 5.01-102-2013 «Foundations of buildings and structures».

Notation	Description	Notes
γ_{c1}	Partial factors on operational conditions	Taken in accordance with Table 4 of SP RK 5.01-102-2013 (Table A1 in Appendices)
γ_{c2}		
k	Dimensionless coefficients	Depends on the method for the determination of soil strength characteristics (φ and c). $k = 1$ for soil properties determined by experimental work, $k = 1.1$ for soil properties taken from table values.
M_γ		Taken in accordance with Table 5 of SP RK 5.01-102-2013 (Figure A1 in Appendices)
M_q		
M_c		
k_z		$k_z = 1$ for $b < 10\ m$, $k_z = \frac{z_0}{b} + 0.2$ for $b \geq 10\ m$ (here $z_0 = 8\ m$)
b	Width of the foundation base (m)	-
γ_{II}	Average soil unit weight under the base of shallow foundation (kN/m^3)	-
γ'_{II}	Average soil unit weight above the base of shallow foundation (kN/m^3)	-
c_{II}	Soil cohesion below the base of shallow foundation (kPa)	-

d_I	Foundation depth (m)	-
d_b	Basement depth (m)	-

European approach requires verification of the following equation to satisfy the ULS design of shallow foundation:

$$V_d \leq R_d \tag{4}$$

where V_d is the vertical action applied on the base of foundation, kN; and R_d is the bearing resistance, kN.

EC 7 provides the following equation for the estimation of the design vertical load applied on the foundation base:

$$V_d = \gamma_G * (G_k + W_{Gk}) + \gamma_Q * Q_k \tag{5}$$

where γ_G is the permanent load partial factor taken from Table 1; G_k is the unfactored permanent load, kN; W_{Gk} is the self-weight of foundation, kN; γ_Q is the variable load partial factor taken from Table 1; and Q_k is the characteristic variable load, kN.

The design procedure for the calculation of bearing resistance of pad and strip foundation adhering to the European approach is described in Annex D of the European code (Eurocode 7, 1997). For the drained conditions, the bearing resistance of the shallow foundation is determined under the Equation 6:

$$R/A' = c'N_c b_c s_c i_c + q'N_q b_q s_q i_q + \frac{1}{2}\gamma' B' N_\gamma b_\gamma s_\gamma i_\gamma \tag{6}$$

Table 4: Description of parameters in Eurocode 7.

Notation	Description	Notes
B'	Width of foundation (m)	-
L'	Length of foundation (m)	-
A'	Design effective area of the foundation (m^2)	$A' = B' * L'$
c'	Design cohesion (kPa)	-

$\boldsymbol{q'}$	Design stress at the foundation base level (kN/m²)	$q' = \gamma' * d$
$\boldsymbol{\gamma'}$	Design unit weight of soil below the foundation level (kN/m³)	-
$\boldsymbol{N_q}$	Dimensionless factors for the bearing resistance	$N_q = e^{\pi tan\varphi'} tan^2\left(\frac{\pi}{4} + \frac{\varphi'}{2}\right)$
$\boldsymbol{N_c}$		$N_c = \left(N_q - 1\right) cot\varphi'$
$\boldsymbol{N_\gamma}$		$N_\gamma = 2\left(N_q - 1\right) tan\varphi'$
$\boldsymbol{b_q}$	Dimensionless factors for the inclination of the foundation base	$b_q = (1 - \alpha tan\varphi')^2$
$\boldsymbol{b_c}$		$b_c = b_q - (1 - b_q)/(N_c tan\varphi')$
$\boldsymbol{b_\gamma}$		$b_\gamma = (1 - \alpha tan\varphi')^2$
$\boldsymbol{s_q}$	Dimensionless factors for the shape of the foundation	$s_q = 1 + (B'/L') sin\varphi'$, for a rectangular shape $s_q = 1 + sin\varphi'$, for a square or circular shape
$\boldsymbol{s_c}$		$s_c = (s_q N_q - 1)/(N_q - 1)$, for a rectangular, square or circular shape
$\boldsymbol{s_\gamma}$		$s_\gamma = 1 - 0.3(B'/L')$, for a rectangular shape $s_\gamma = 0.7$, for a square or circular shape
$\boldsymbol{i_c}$	Dimensionless factors for the inclination of the load caused by horizontal load H	$i_c = i_q - 1(1 - i_q)/\ N_c tan\varphi')$
$\boldsymbol{i_q}$		$i_q = [1 - \frac{H}{V + A'c'cot\varphi'}]^m$
$\boldsymbol{i_\gamma}$		$i_\gamma = [1 - \frac{H}{V + A'c'cot\varphi'}]^{m+1}$ where: $m = m_B = \ [2 + (B'/L')]/[1 + (B'/L')]$ when H acts in the direction of B'; $m = m_L = \ [2 + (L'/B')]/[1 + (L'/B')]$ when H acts in the direction of L'.

α	Inclination of the foundation base to the horizontal	-

3.3.2 Determination of the elastic settlement of shallow foundation

The procedure for the computation of the immediate settlement of pad and strip foundations is given in SP RK 5.01-102-2013 «Foundations of buildings and structures» (SP RK, 2015a). The Kazakhstani approach applies the layer-by-layer summation method for settlement calculation as follows:

$$s = \beta \sum_{i=1}^{n} \frac{\sigma_{zp,i} \cdot h_i}{E_i} \tag{7}$$

Table 5: Description of parameters in SP RK 5.01-102-2013 «Foundations of buildings and structures».

Notation	Description	Notes
$\boldsymbol{\beta}$	Dimensionless coefficient	Taken equal to 0.8
$\boldsymbol{\sigma_{zp,i}}$	Average vertical stress value in the i-th soil layer (kPa)	-
$\boldsymbol{h_i}$	Thickness of the i-th soil layer (cm)	Taken as not more than 0.4 of the foundation width
$\boldsymbol{E_i}$	Deformation modulus of the i-th soil layer (kPa)	-
$\boldsymbol{n}$	Number of layers in the considered soil profile	

The elastic settlement of raft foundation adhering to the Kazakhstani approach is determined by the application of the following equation:

$$s = \frac{pbk_c}{k_m} \sum \frac{k_i - k_{i-1}}{E_i} \tag{8}$$

where p is the average pressure acting under the foundation base (kPa); b is the raft foundation width (m); k_c, k_m, and k_i are the dimensionless coefficients; and E_i is the modulus of elasticity (kPa).

The method for the calculation of the elastic settlement of shallow foundation on cohesive and non-cohesive soil based on the adjusted elasticity theory is provided in Annex F of EC 7 (Eurocode 7, 1997). The following equation is used for the calculation of the total settlement of shallow foundation adhering to the European approach:

$$s = pBf/E_m \tag{9}$$

Table 6: Description of parameters in Eurocode 7.

Notation	Description	Notes
p	Net bearing pressure linearly distributed on the foundation base (kPa)	-
f	Settlement coefficient	$f = (1 - v^2)I_p$ where v is the Poisson's ratio of soil, and I_p is the influence factor for settlement.
E_m	Design modulus of soil deformation (kPa)	

3.4 Deep foundation design

The foundation type that transfers the load from the building to the ground at a depth greater than its least dimension (Smith, 2014). Pile and piled raft foundations are categorized as deep foundations.

3.4.1 Determination of the bearing resistance of deep foundation

The design procedure for pile foundation adhering to the Kazakhstani approach is given in SP RK 5.01-103-2013 «Pile foundations» (SP RK, 2015b). The following condition is required to be satisfied for a single pile design:

$$N \leq \frac{F_d}{\gamma_k} \tag{10}$$

Table 7: Description of parameters in SP RK 5.01-103-2013 «Pile foundations».

Notation	Description	Notes

$\boldsymbol{N}$	Design load acting on a single pile (kN)	-
$\boldsymbol{F_d}$	Design bearing resistance of soil at the pile base (kN)	Considered as pile bearing resistance
$\boldsymbol{\gamma_k}$	Reliability coefficient	$\gamma_k = 1.2$ if pile bearing resistance is determined based on the field testing results (static pile load testing); $\gamma_k = 1.25$ if pile bearing resistance is determined based on the field testing results (dynamic pile load testing); $\gamma_k = 1.4$ if pile bearing resistance is determined based on calculation results.

The bearing resistance of a single pile is determined as the summation of soil resistance under the pile base and at its shaft surface in accordance with the following equation:

$$F_d = \gamma_c(\gamma_{cR}RA + u\sum \gamma_{cf} f_i h_i) \tag{11}$$

Table 8: Description of parameters in SP RK 5.01-103-2013 «Pile foundations».

Notation	Description	Notes
$\boldsymbol{\gamma_c}$	Partial factor on operational conditions	Taken from Table 8 of SP RK 5.01-103-2013
$\boldsymbol{R}$	Design resistance of soil under the pile base (kPa)	Taken from Table 1 of SP RK 5.01-103-2013 (Figure A2 in Appendices)
$\boldsymbol{A}$	Cross-sectional area of pile base (m^2)	-
$\boldsymbol{u}$	Outer perimeter of pile shaft (m)	-
$\boldsymbol{f_i}$	Design resistance of i-th soil layer at the pile shaft (kPa)	Taken from Table 2 of SP RK 5.01-103-2013 (Figure A3 in Appendices)

$\boldsymbol{h_i}$	Thickness of i-th soil layer in contact with the pile shaft (m)	-
$\boldsymbol{\gamma_{cR}}$	Partial factor on operational conditions of soil under the pile base	Taken from Table 3 of SP RK 5.01-103-2013
$\boldsymbol{\gamma_{cf}}$	Partial factor on operational conditions of soil at the pile shaft surface	

Section 7 of EC 7 (Eurocode 7, 1997) describes the procedure for the design of pile foundation adhering to the European approach. The general ULS design condition requires the load applied on the pile foundation, V_d, to be less or equal to the design bearing resistance, R_d, to ensure adequate safety and stability of the designed structure. Equation 5 provides the formula for the calculation of the vertical load acting on the foundation.

The design resistance of pile foundation is determined using the following equation:

$$R_{c;d} = \frac{R_{b;k}}{\gamma_b} + \frac{R_{s;k}}{\gamma_s} \tag{12}$$

where $R_{b;k}$, $R_{s;k}$ are the characteristic values of the base and shaft resistances, respectively, kN; and γ_b, γ_s are the partial factors of the base and shaft resistances, respectively, for driven piles provided in Table 1.

The characteristic values of the base and shaft resistances are determined from the following equations:

$$R_{b;k} = A_b q_{b;k} \tag{13}$$

$$R_{s;k} = \sum A_{s;i} q_{s;i;k} \tag{14}$$

where $q_{b;k}$, $q_{s;i;k}$ are the characteristic values of the unit base and shaft resistances, respectively, kN/m^2; A_b is the pile base area, m^2; and $A_{s;i}$ is the pile shaft area in i-th soil layer, m^2.

Piled raft foundation represents a composite structure widely applied around the world for the construction of multi-storey buildings/high-rise buildings in recent years (Reul & Randolph, 2009). The performance of raft foundation is enhanced by adding piles in piled raft foundation by (1) increasing the load capacity, (2) decreasing the foundation settlement, and (3) reducing the construction cost without any negative effect on the foundation performance and safety (Poulos, 2001).

Both the Kazakhstani and European approaches calculate the bearing resistance of piled raft foundation by way of the summation of raft resistance, R_{raft}, and resistance of piles, $R_{pile,i}$, using the following equation (Katzenbach et al., 2005):

$$R_{tot} = \sum R_{pile,i} + R_{raft} \quad (15)$$

3.4.2 Determination of the elastic settlement of deep foundation

The procedure for the determination of the elastic settlement of a single pile adhering to the Kazakhstani approach is outlined in Annex G of SP RK 5.01-103-2013 «Pile foundations» (SP RK, 2015b). The elastic settlement of a single pile is calculated using the following equation:

$$s = \beta \frac{N}{G_1 l} \quad (16)$$

Table 9: Description of parameters in SP RK 5.01-103-2013 «Pile foundations».

Notation	Description	Notes
$\boldsymbol{N}$	Vertical load applied on a single pile (MN)	-
$\boldsymbol{G_1}$	Shear modulus of soil (MPa)	-
$\boldsymbol{l}$	Pile length (m)	-
$\boldsymbol{\beta}$	Dimensionless coefficient	$\beta = \frac{\beta'}{\lambda_1} + \frac{1 - (\beta'/\alpha')}{\chi}$ where β' is the coefficient corresponding to the absolutely rigid pile ($EA = \infty$); λ_1 is the parameter characterizing the settlement increase due to the compression of pile shaft.

The elastic settlement of piled raft foundation adhering to the Kazakhstani approach is determined using the following equation:

$$s_f = \gamma_f * \frac{\sum P}{K_f} \tag{17}$$

where γ_f is the safety factor equal to 1.2; P is the vertical action applied on the designed piled raft foundation, kN; and K_f is the total stiffness of the designed piled raft foundation, kN/m, equal to the summation of the stiffnesses of the raft and all piles.

The European approach applies the elasticity theory for the elastic settlement of a single pile estimation using the following equation (Poulos & Davis, 1980):

$$s = \frac{P}{dE_s} I_p \tag{18}$$

where P is the vertical load acting on pile foundation, kN; d is the diameter of a single pile, m; E_s is the soil deformation modulus, MPa; and I_p is the displacement influence factor of a single pile.

When adhering to the European approach, the elastic settlement of piled raft foundation is calculated under the following equation (Randolph, 1994):

$$s = \frac{P}{K_{PR}} \tag{19}$$

Table 10: Description of parameters in Eurocode 7.

Notation	Description	Notes
$\boldsymbol{P}$	Vertical load applied on the piled raft foundation (kN)	-
$\boldsymbol{K_{PR}}$	Stiffness of the piled raft foundation (kN/m)	$K_{PR} = \frac{K_{PG} + (1 - 2\alpha_{rp})K_R}{1 - \alpha_{rp}^2(\frac{K_R}{K_{PG}})}$ where K_{PR}, K_{PG}, K_R are the stiffness of piled raft, pile group, and raft, respectively (kN/m); α_{rp} is the raft-pile interaction factor.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

Alibekova and Zhussupbekov (2018) provided the Nur-Sultan site investigation data including the information on soil profiles and engineering properties of the city. Using the "Geographic information database", the territory of Nur-Sultan city has been divided into three uniform zones based on the soil profile types as shown in Figure 5.

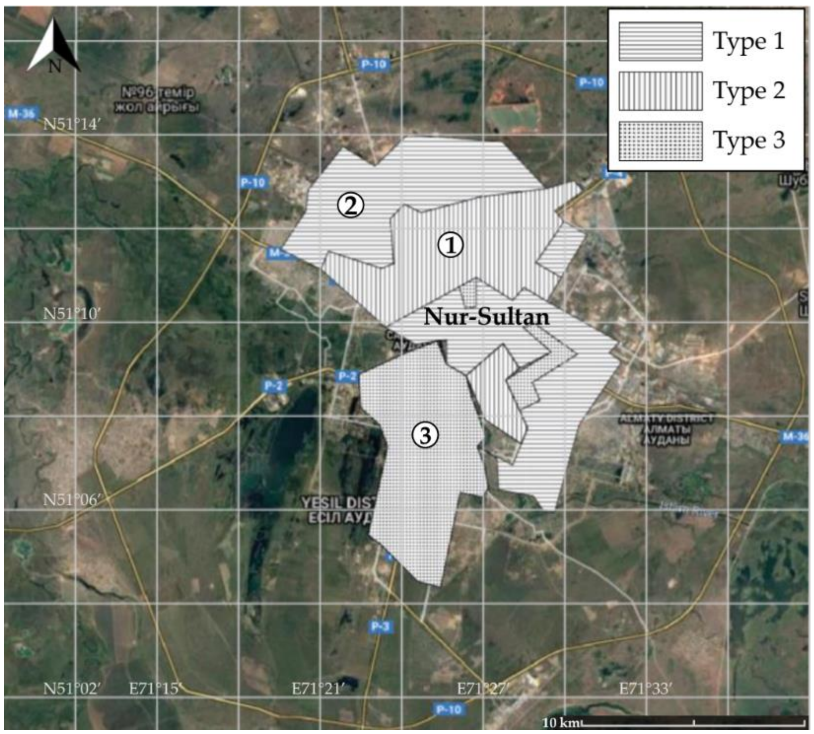


Figure 5: Zoning of Nur-Sultan territory based on the soil profile types

Three soil layers, such as loam, sandy gravel, and clay, represent the soil profile of Nur-Sultan. The soil engineering properties for Nur-Sultan soil are summarized in Table 11.

Table 11: Soil engineering properties of Nur-Sultan soil

Soil Type	Loam	Note
Water content (w), %	19.10	Obtained from Alibekova and Zhussupbekov (2018)
Effective friction angle, (φ’), °	22.00	
Modulus of deformation (E), MPa	7.00	
Liquid limit (LL), %	30.00	
Plastic limit (PL), %	18.00	
Plasticity index (PI), %	12.00	
Liquidity index (LI)	0.09	
Unit weight (γ), kN/m^3	19.42	
Saturated unit weight (γ_{sat}), kN/m^3)	20.10	
Effective cohesion (c’), kPa	15.00	
Undrained shear strength (c_u), kPa	118.00	Determined as the average value of Cangir and Dipova (2017), Schofield and Wroth (1968), Wroth and Wood (1978)

The example given in this study is presented to compare the Kazakhstani and European approaches from the point of their conservativeness for shallow and deep foundation design in Nur-Sultan city. Two design problems provided in Figures 6 and 7 require calculating the bearing resistance and elastic settlement for a long-term condition of shallow and deep foundations, respectively. The groundwater table (G.W.T.) is assumed to be placed at a 2 m depth under the existing soil surface (Alibekova and Zhussupbekov, 2018). The standard structure condition implies the ratio of variable load to permanent load to be 0.25 ($Live\ Load = 0.25 * Dead\ Load$). For the simplified analysis, the load eccentricity is neglected.

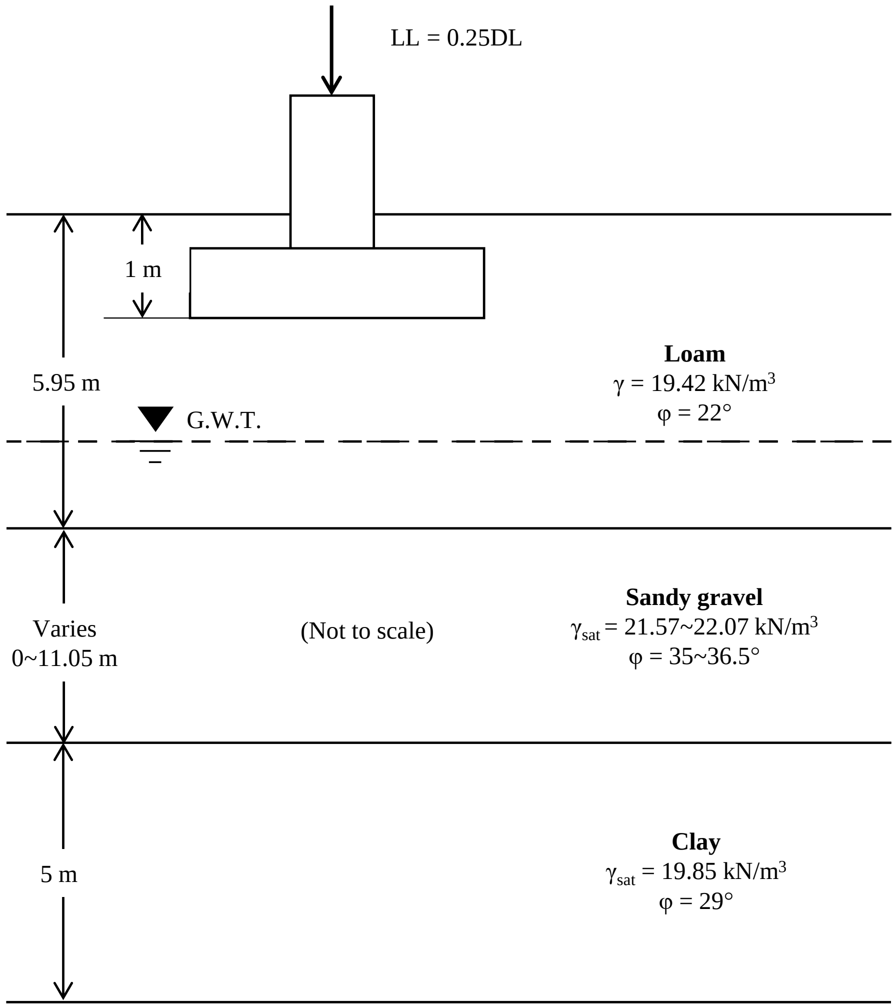


Figure 6: Idealized soil profile and designed strip and pad foundations

In Figure 6, the bearing resistance and elastic settlement are asked to be identified for two different shallow foundation types (strip foundation of width=2 m and length=10 m and pad foundation of width=1.5 m and length=2 m) when adhering to SP RK and EC7. The foundation depth for both pad and strip is located at a 1 m depth under the ground surface.

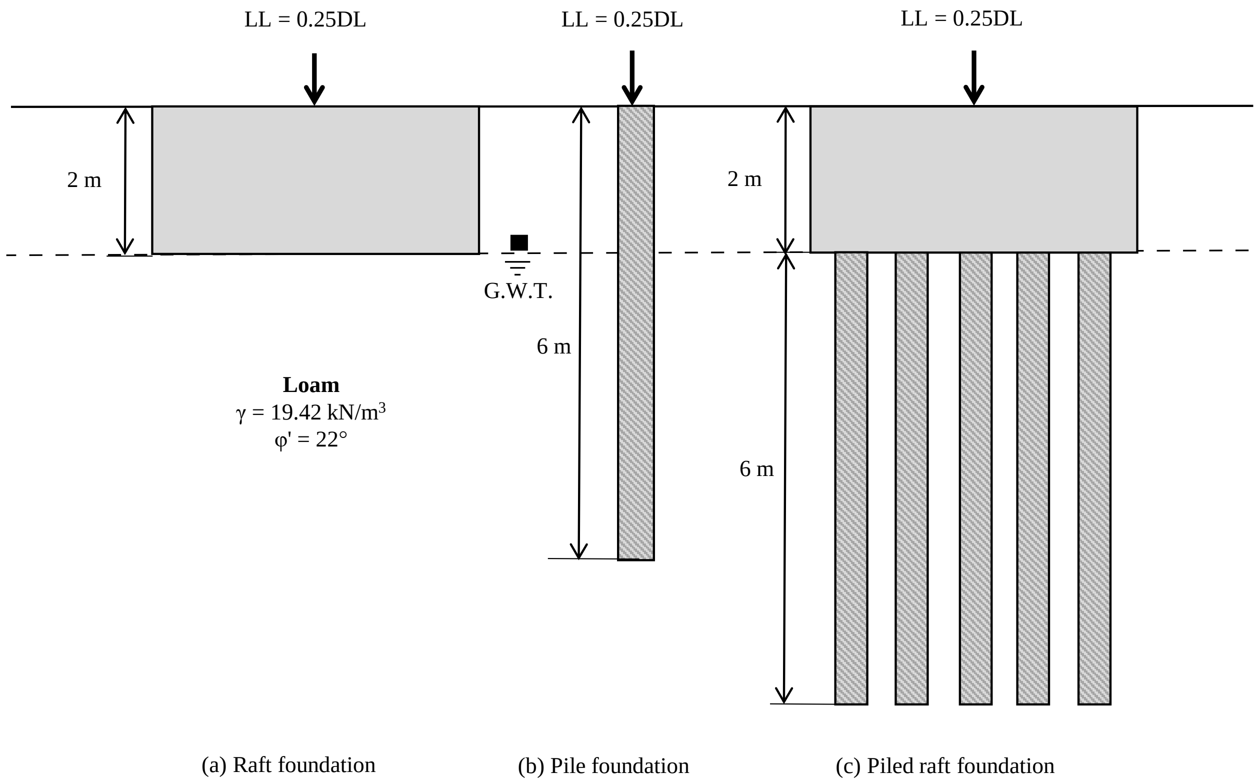


Figure 7: Idealized soil profile and designed raft, pile, and piled raft foundations

In Figure 7, the comparative analysis of the Kazakhstani and European approaches is asked to be performed for a raft foundation with length 20 m and width 10 m, a concrete driven square pile foundation with cross-sectional area 300 mm × 300 mm and length 6 m, and a piled raft foundation representing the combination of the first two foundations. The piles are driven by hydraulic and diesel hammers.

4.2 Results for shallow foundation

Table 12 provides the values of permanent and variable vertical loads for shallow foundations required for the determination of bearing resistance and elastic settlement when adhering to the Kazakhstani and European approaches. The values of factored vertical loads acting on the foundation base are calculated with the application of partial factors from EC7 and SP RK. The obtained results of the vertical load applied on shallow foundations allow the calculation of bearing resistance and elastic settlement for SP RK and EC7.

Table 12: Loads applied on shallow foundations

Applied loads	Pad foundation	Strip foundation
Permanent load (kN)	493	3580
Variable load (kN)	123	895

4.2.1 Over-design factor

The comparative analysis of the considered design codes in terms of their conservativeness is performed by the determination of over-design factor (ODF). The ODF represents the safety level for the designed foundations, and it can be calculated using the following equation:

$$ODF = \frac{R_d}{E_d} \geq 1 \quad (20)$$

where R_d is the bearing resistance, kN, and E_d is the applied vertical load, kN. The geotechnical ULS is fulfilled with Equation 20.

The vertical load acting on the design foundations adhering to EC7 is determined by the fact that SP RK ODF is equal to 1.0. Considering the design condition of the standard structure ($Live\ Load = 0.25 * Dead\ Load$), the permanent and variable loads acting on pad and strip foundations are calculated. The obtained results were applied for the determination of ODF values provided in Figure 10. The ODF calculation results shows 1.32 to 1.85 and 1.12 to 1.57 times higher values for the European approach than for the Kazakhstani approach for pad and strip foundations, respectively. The difference between ODF results is attributed to the appliance of partial factors on permanent and variable loads when calculating the design resistance, R_d, for EC7.

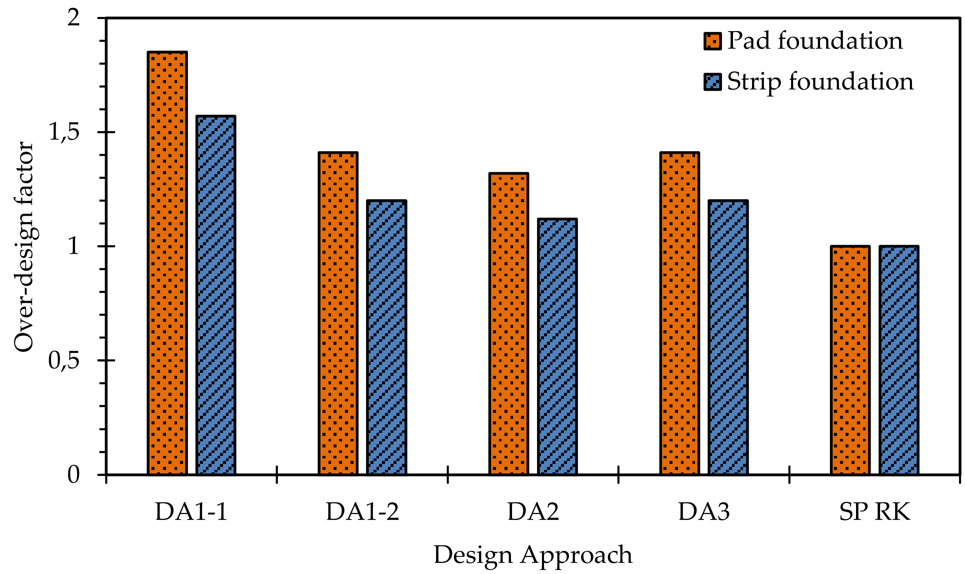


Figure 8: Over-design factor of shallow foundation adhering to the Kazakhstani and European approaches

4.2.2 Bearing resistance

The design bearing resistance of pad and strip foundations was identified with the application of Equations (3) and (6) adhering to the Kazakhstani and European approaches, respectively. The results of the bearing resistance of shallow foundations applying the considered codes of practice are presented in Figure 8. The obtained results of the bearing resistance of strip and pad foundations show relatively comparable values for the Kazakhstani and European regulations. Nevertheless, it is observed that the bearing resistance values from EC 7 exceed the SP RK values. The European approach provides 1.6 to 2.7 and 1.4 to 2.4 times greater results of bearing resistance than the Kazakhstani approach for pad and strip foundations, respectively. Obtaining the higher bearing resistance refers to the use of higher partial factors when adhering to the European approach. However, both of the design codes apply dimensionless coefficients on effective cohesion, overburden pressure, and unit weight of soil for the design of shallow foundations (i.e., M_{γ}, M_{q}, and M_{c} by SP RK and $N_{\gamma}b_{\gamma}s_{\gamma}i_{\gamma}$, $N_{q}b_{q}s_{q}i_{q}$, and $N_{c}b_{c}s_{c}i_{c}$ by EC 7). As Nur-Sultan soil represents cohesive soil, the difference between the design codes refers to the parameters used in the foundation design. In particular, the Kazakhstani approach considers the liquidity index when calculating the bearing resistance of shallow foundations (Figures A2 and A3), whereas the European approach considers the undrained shears strength of the soil.

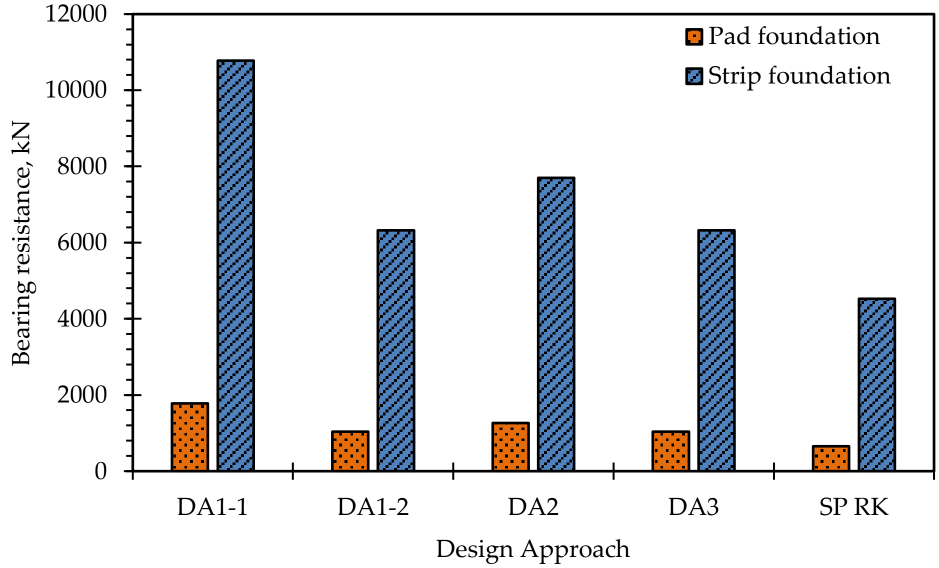


Figure 9: Bearing resistance of shallow foundation adhering to the Kazakhstani and European approaches

4.2.3 Elastic settlement

Figure 9 shows the calculated values of the elastic settlement when adhering to the Kazakhstani and European approaches. The difference between the obtained EC7 and SP RK results is obtained due to the application of different design methods by the considered codes of practice. The elastic settlement is calculated using the adjusted elasticity theory by EC7 in accordance with Equation (9), whereas the Kazakhstani building regulation applies the layer-by-layer summation method in accordance with Equation (7). The performed calculations show the same values of the elastic settlement for all European DAs (i.e., DA1-1, DA1-2, DA2, and DA3) for both pad and strip foundations. However, it is observed that the Kazakhstani approach gives the lower values of the elastic settlement compared to the European approach.

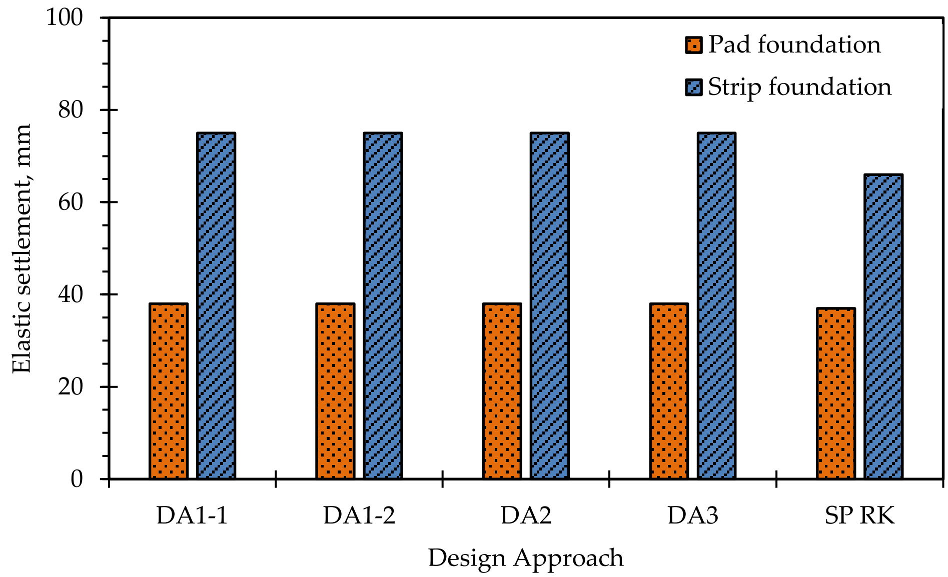


Figure 10: Elastic settlement of shallow foundation adhering to the Kazakhstani and European approaches

4.3 Results for pile foundation

Table 13 provides the values of the unfactored permanent and variable load acting on the raft and pile foundations required for the determination of bearing resistance and elastic settlement when adhering to the Kazakhstani and European approaches. The values of factored vertical loads acting on the foundation base are calculated with the application of partial factors from EC7 and SP RK. The obtained values of the vertical load acting on the designed foundations allow the determination of the bearing resistance and elastic settlement values for SP RK and EC7.

Table 13: Loads applied on deep foundations

Applied loads	Raft foundation	Pile foundation
Permanent load (kN)	60,500	240
Variable load (kN)	15,100	60

4.3.1 Over-design factor

The vertical load acting on the design foundations adhering to EC7 is determined assuming the ODF for SP RK to be equal to unity. Considering the design condition of the standard structure ($Live\ Load = 0.25 * Dead\ Load$), the permanent and variable loads acting on pad and strip foundations are calculated. As discussed in Section 4.2.1, the ODF of the raft and pile foundations is for the European and Kazakhstani approaches is calculated by using Equation 19. The obtained values of ODF from the design approaches (i.e., DA1-1, DA1-2, DA2, and DA3) of EC7 and SP RK are provided in Figure 11. ODF for the Kazakhstani approach is assumed to be equal to unity, whereas the European approach resulted in 6% to 38% higher values for both raft and pile foundations. As explained in Section 4.2.1, the difference is obtained due to the higher factored vertical load for the calculation of the design resistance, R_d, by EC7.

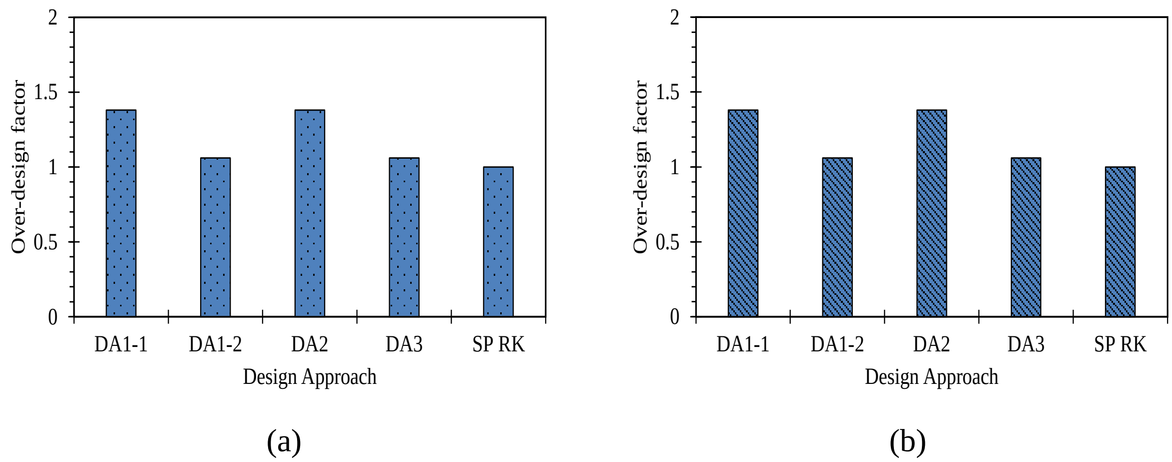
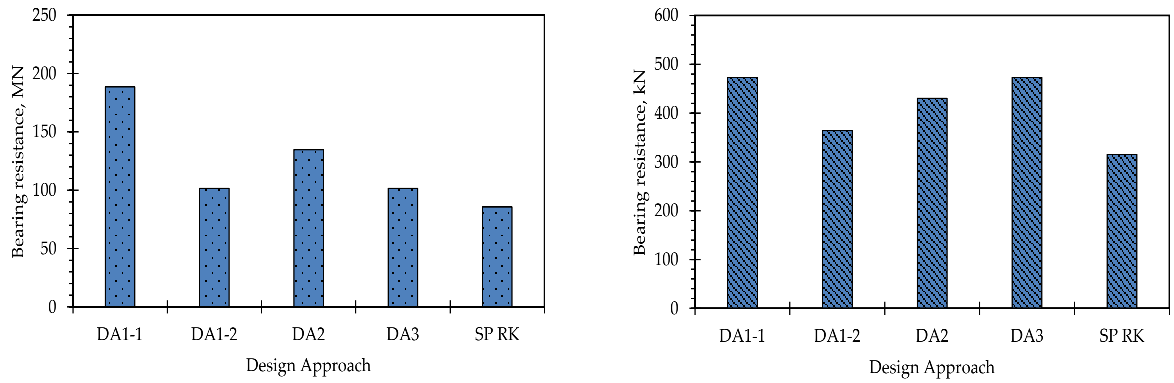


Figure 11: Over-design factor of (a) raft foundation and (b) pile foundation adhering to the Kazakhstani and European approaches

4.3.2 Bearing resistance

The obtained results of bearing resistance of raft and pile foundations are provided in Figure 12. The design procedure for the determination of the bearing resistance of shallow foundation (i.e., raft foundation), as well as the differences between the Kazakhstani and European approaches, are discussed in Section 4.2.2. For both the Kazakhstani and European approaches, the bearing resistance of pile foundation is presented as the summation of pile base and shaft resistances as given in Equations 11 and 12, respectively. However, the difference refers to the application of different partial safety factors by the design codes. For the determination of bearing resistance of pile foundation, SP RK applies partial factors on operational conditions under the base and the shaft surface of the pile (i.e., γ_{cR} and γ_{cf}), whereas EC 7 applies partial factors on base and shaft resistances (i.e., γ_b and γ_s). Moreover, the reduction factor is used for the calculation of the bearing resistance by the Kazakhstani approach as given in Equation 10, while the European approach directly determines the factored bearing resistance of pile foundation by the application of factored strength parameters. Referring to Figure 12, it is obtained that EC7 results of bearing resistance exceed SP RK values by 1.2 to 2.2 and 1.15 to 1.5 times for raft and pile foundations, respectively.



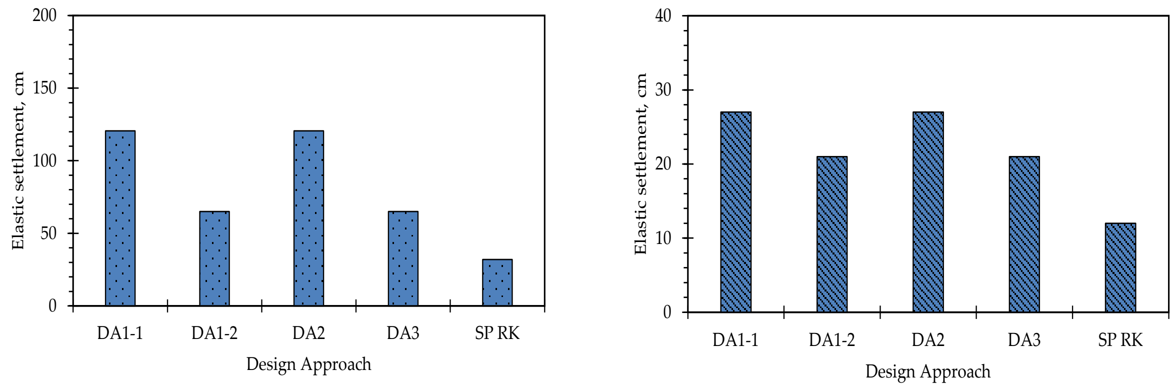
(a) (b)

Figure 12: Bearing resistance of (a) raft foundation and (b) pile foundation adhering to the Kazakhstani and European approaches

As indicated in Equation (15), the bearing resistance of piled raft foundation is determined as the combination of design resistances of the raft and pile foundations. Based on the obtained results of bearing resistances of the raft and pile foundations, the design resistance of piled raft foundation results in 93,000 kN for both design approaches. The raft element of piled raft foundation contributes to the increase of the design resistance at the ultimate limit state (ULS).

4.3.3 Elastic settlement

The obtained values of elastic settlement for raft and pile foundations adhering to the Kazakhstani and European approaches are given in Figure 13. The elastic settlement of raft foundation is determined by SP RK and EC7 using Equations (8) and (9), respectively. The Kazakhstani building regulation applies the linearly deformable method for the determination of the elastic settlement of raft foundation, whereas EC7 uses the adjusted elasticity theory. Both of the design methods consider the application of settlement coefficient, the value of which depends on the foundation parameters. The comparative analysis revealed that the Kazakhstani approach involves the application of shear modulus when calculation the elastic settlement of pile foundation as provided in Equation (16), whereas the European approach considers the elasticity modulus as given in Equation (18). Referring to Figure 16, it is identified that the elastic settlement calculated by EC7 is higher by 2.0 to 3.8 and 1.7 to 2.3 times than SP RK values for raft and pile foundations, respectively.



(a) (b)

Figure 13: Elastic settlement of (a) raft foundation and (b) pile foundation adhering to the Kazakhstani and European approaches

Based on the obtained results of bearing resistance of piled raft foundation, the determination of the elastic settlement of piled raft foundation adhering to the Kazakhstani and European approaches is performed. Both SP RK and EC7 apply the stiffness method for the estimation of the elastic settlement. The stiffness method involves the stiffness of the piled raft foundation as indicated in Equation (17) for SP RK (i.e., K_f) and Equation (19) for EC 7 (i.e., K_{PR}). The comparison of the elastic settlement of piled raft foundation shows 15 cm for the Kazakhstani approach and 26 cm for the European approach. The pile group element of the piled raft foundation ensures the reduction in the elastic settlement.

4.4 Comparison of the design results adhering to Kazakhstani and European approaches

Both the Kazakhstani and European approaches perform the design of shallow and deep foundations in accordance with the limit state analysis. The advantage of Eurocode is related to the consideration of not only static and dynamic loads but also serviceability load by the application of partial factors of safety. Thus, the design results obtained using EC7 exceed the SP RK, which means that Eurocode provides more stability, safety, and durability to the designed buildings and structures.

The comparative analysis of the design codes shows that the differences are mainly related to the application of different values of partial safety factors, as well as the introduction of different design methods for the construction of buildings and structures. The higher values of partial safety factors applied by EC7 are obtained due to the difference in climatic and geophysical characteristics considered when developing the design codes. Moreover, the obtained higher values of the vertical load by the European approach contributed to the higher values of both bearing resistance and elastic settlement of shallow and deep foundations. Therefore, it can be concluded that the European approach provides more conservative results than the Kazakhstani approach for both shallow and deep foundations.

The results of sensitivity analysis are provided in Figures 14 and 15 to show the effect of varying foundation parameters on the bearing resistance value. The design resistance of raft and pile foundations is estimated adhering to the Kazakhstani and European approaches for varying widths (2–20 m) of raft foundation and lengths (3–15 m) of pile foundation. It can be observed that DA1-2 and DA3 provide the same results of bearing resistance for both raft and pile foundations due to the application of the same values of partial safety factors. Figure 14 revealed 1.7 to 2.9, 1.0 to 1.5, and 1.2 to 2.1 times higher values of raft foundation bearing resistance of DA1-1, DA1-2 and DA3, and DA2 of EC 7 compared to SP RK results, respectively. Also, Figure 15 shows 1.3 to 1.4, 1.0 to 1.1, and 1.2 to 1.3 times differences between DA1-1, DA1-2 and DA3, and DA2 of EC 7 and SP RK values of bearing resistance of pile foundation, respectively.

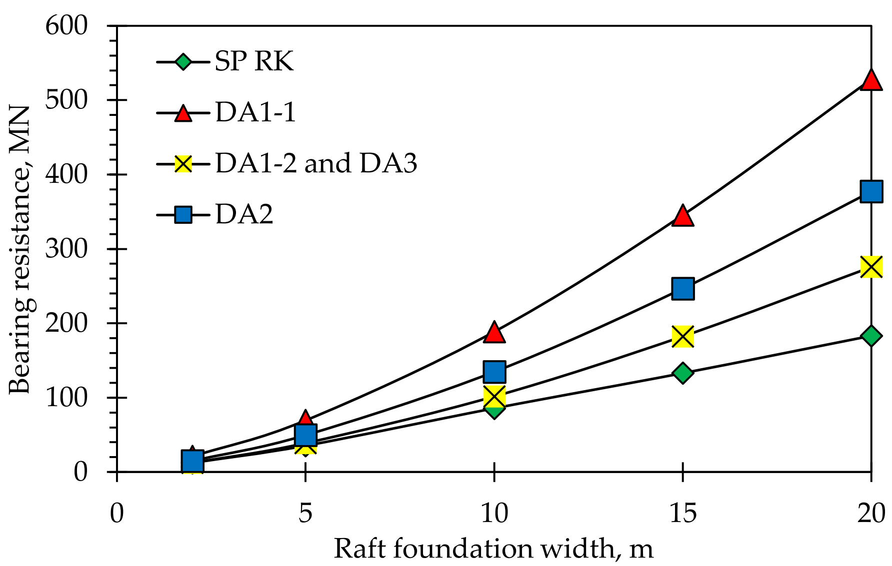


Figure 14: Bearing resistance for varying widths of raft foundation

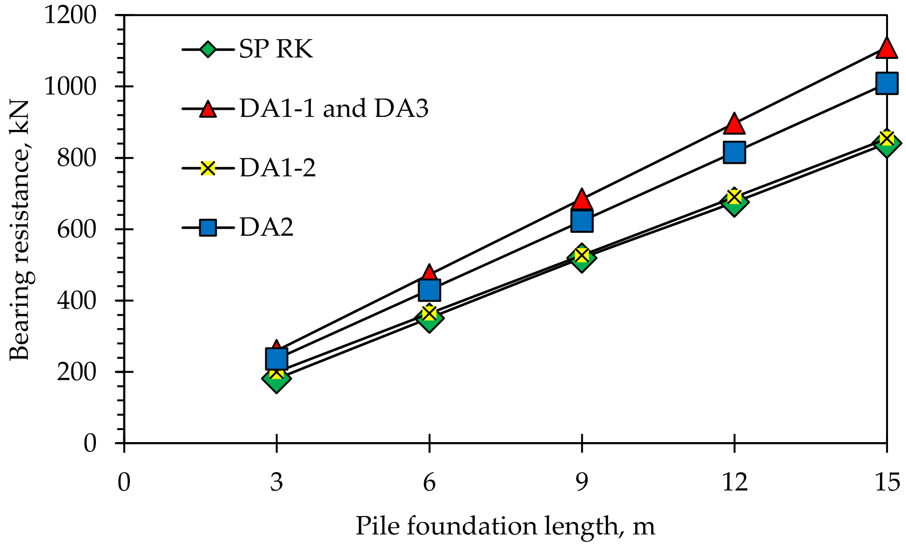


Figure 15: Bearing resistance for varying lengths of pile foundation

When compared to the Kazakhstani building regulation it can be observed that EC7 provides more conservative results, thus ensures higher safety level and guaranteed durability of the designed structures.

CHAPTER FIVE: CONCLUSIONS

5.1 Limitations of the study

This section presents the limitations of the comparison of the Kazakhstani and European approaches for geotechnical design of shallow and deep foundations that are listed as follows:

- Assumed fixed groundwater table (G.W.T.) over the all designed territory – the groundwater table depth in Nur-Sultan is very shallow and varies from 1.5 to 3 m on the territory of the city. Therefore, the average value of G.W.T. is assumed for the geotechnical design of foundations.
- Constant soil profile – The soil profile of Nur-Sultan is mainly presented by loam, sandy gravel, and clay soils. However, for the design simplicity, the other soil types are not considered in the calculations.
- The applied value of the undrained shear strength – The European approach considers the undrained shear strength value for the design of pile foundations. As this value has not been identified empirically, the average of Cangir and Dipova (2017), Schofield and Wroth (1968), Wroth and Wood (1978) is used in the design.
- Standard structure condition – The standard structure condition considered for the foundation design assumed the ratio of variable load to permanent load to be 0.25 ($Live\ Load = 0.25 * Dead\ Load$).
- The limited number of the design cases – The conclusions regarding the conservativeness of EC 7 and SP RK for shallow and pile foundation design are made on the basis of limited design cases. Therefore, the further comparative study is for more accurate research results.

5.2 Conclusions

The governmental decision on the transition from the Kazakhstani building regulation (SP RK) to Eurocode 7 has been made to increase the quality of the construction works in the country, as well as positively contribute to the development of the construction sector. The adaptation of Eurocode in Kazakhstan allows establishing the uniform framework for the realization of complex construction projects, as well as the elimination of technical and documentary barriers with foreign colleagues. Additionally, the introduction of Eurocode in Kazakhstan facilitates scientific collaboration with European countries by the application of identical methods and requirements and obtaining identical calculation results for the performance of geotechnical design of buildings and structures.

The harmonization of EC with the Kazakhstani building regulation is aimed to attract foreign investments for the realization of international projects, as well as integrate into the European economy. This requires the performance of the comparative analysis of the design values, translation of EC into the country's language, and development of National Annex (NA). The development of the NA of Kazakhstan must cover climatic, geophysical, and seismic characteristics of the country, which are significantly different from the EU-countries. It is of high significance to understand that transition will take great efforts to shift to the European approach by avoiding misunderstanding the design principles.

This research work presents the design of shallow and deep foundations (raft, pile, pad, strip, and piled raft) through the comparison of the Kazakhstani and European geotechnical design approaches. The shallow and deep foundations design procedure for estimation of over-design factor, bearing resistance, and elastic settlement adhering to national building regulation and EC7 is explained. Through the comparison of the studied codes of practice is accomplished by the consideration of the design problem in Nur-Sultan, Kazakhstan. It can be concluded that the differences between the design processes for the computation of design action, bearing resistance, and elastic settlement of shallow and deep foundations applied by both Kazakhstani and European approaches exist. Compared to SP RK, EC7 provides general guidance and all design details are decided referring to NA. Therefore, the European approach provides more flexibility for the application, whereas the Kazakhstani approach limits the application of innovative construction technologies and materials and minimizes the safety factor of the designed buildings and structures.

The performed calculations allowed obtaining the over-design factor (ODF), bearing resistance, and elastic settlement of pad, strip, raft, pile, and piled raft foundations adhering to the Kazakhstani and European approaches. The obtained computational results revealed EC7 values always exceed SP RK values. The employment of higher values of partial factor parameters by EC7 is among the reasons for getting higher design results. Moreover, the fact that the European approach combines the design traditions and practices of the European countries affects the conservativeness of this design code. It can be concluded that the European approach provides more conservative results in contrast with the Kazakhstani approach for the design of shallow and deep foundations. The conclusions of the study are also supported by the performed sensitivity analysis for the bearing resistance calculation for the varying foundation shape parameters (i.e., width of the raft foundation and pile length). Further analysis on the comparison of the design codes is required to enhance the study conclusions.

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Appendix

Table A1: Coefficients γ_{c1} and γ_{c2}

Soil type	Coefficient γ_{c1}	Coefficient γ_{c2} for buildings and structures with the ratio L/H equal to	
		4 and more	**1.5 and less**
Coarse-grained soil with sandy aggregates and sand	1.4	1.2	1.4
Fine sand	1.3	1.1	1.3
Silty sand: unsaturated saturated	 1.25 1.1	 1.0 1.0	 1.2 1.2
Clay with $I_L \leq 0.25$	1.25	1.0	1.1
Clay with $0.25 < I_L \leq 0.55$	1.2	1.0	1.1
Clay with $I_L > 0.5$	1.0	1.0	1.0

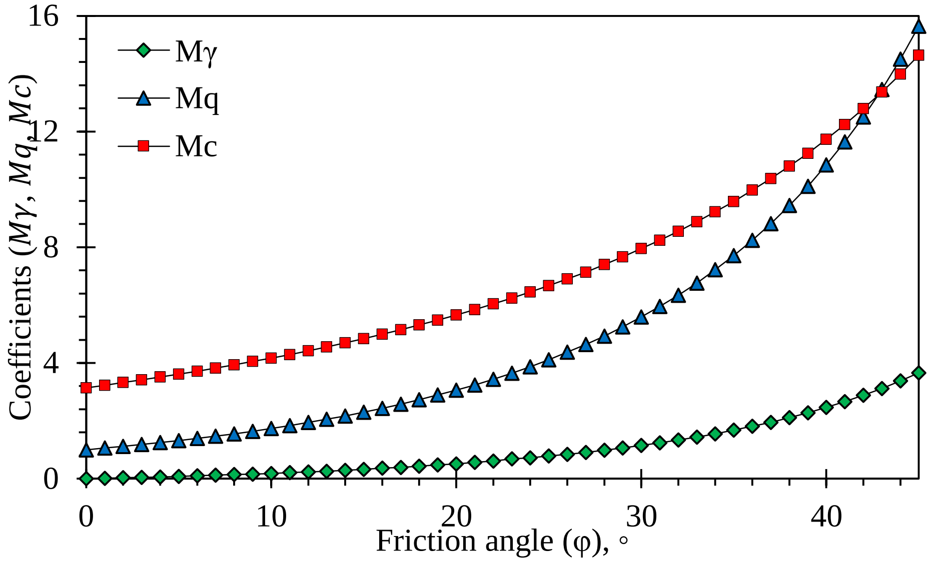

Figure A1: Coefficients M_γ, M_q, M_c

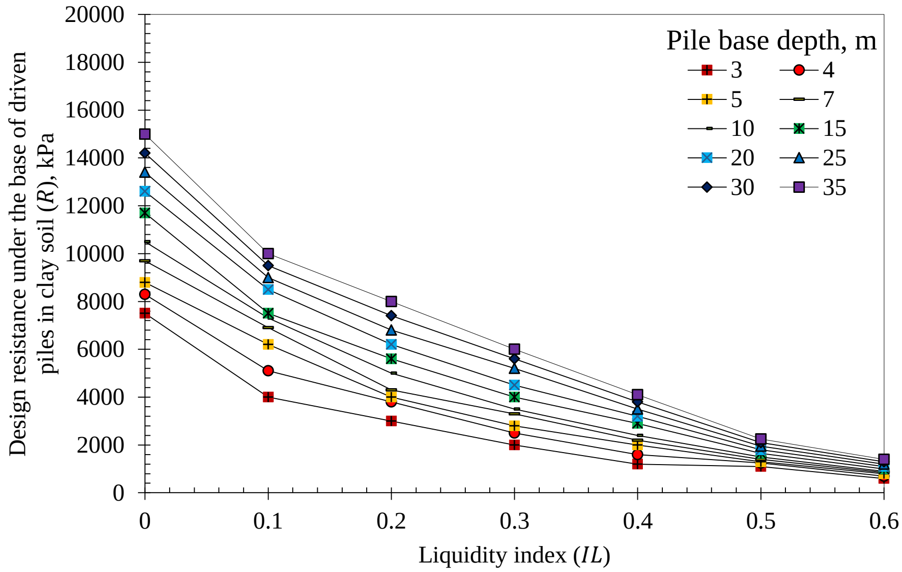

Figure A2: Design resistance of soil under the pile base, R

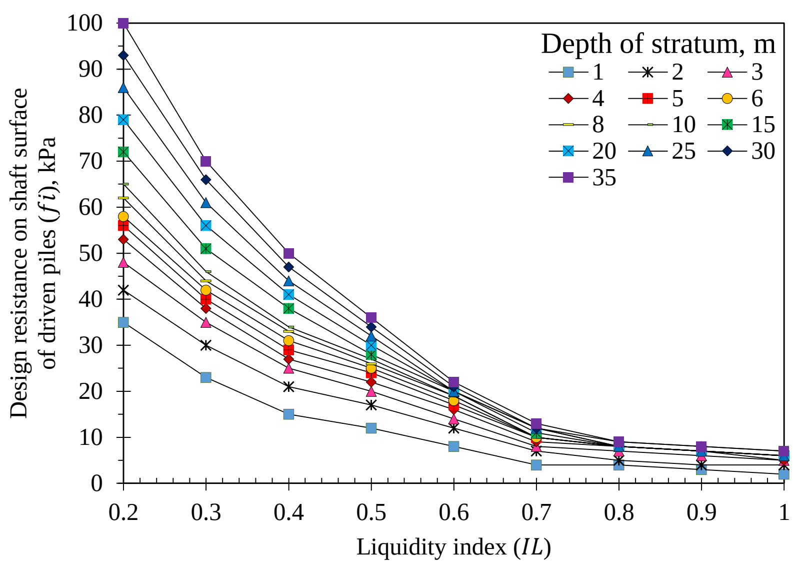

Figure A3: Design resistance of soil at the pile shaft, f_i